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14. ABSTRACT

Future aircraft may utilize the large aerodynamic areas of the wings for electrodynamics by structurally embedding conformal phased array antennas. We explore this concept with a computer model for a line array wrapped around a wing. The model uses a realistic wing profile and array element patterns which include the effects of mutual coupling and the local radius of curvature. The study has two objectives: 1) demonstrate a pattern synthesis method for this non-conventional array shape, and 2) determine whether low sidelobe patterns can be realized. We find pattern synthesis based on altering projections is a flexible and highly efficient synthesis method. High quality patterns with uniform low sidelobes achieved for most beam directions, except in a narrow sector about the difficult forward direction, where there appears to be a sidelobe floor of roughly -23dB.

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Pattern Synthesis for a Conformal Wing Array

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Abstract — Future aircraft may utilize the large aerodynamic areas of the wings also for electrodynamics by structurally embedding conformal phased array antennas. We explore this concept with a computer model for a line array wrapped around a wing. The model uses a realistic wing profile and array element patterns which include the effects of mutual coupling and the local radius of curvature. The study has two objectives: 1) develop a pattern synthesis method which is effective for this non-conventional array shape, and 2) determine whether low sidelobe patterns can be realized.

We find that pattern synthesis based on alternating projections is a flexible and highly efficient synthesis method. No convergence problems due to local minima occurred. High quality patterns with uniform low sidelobes were achieved for most beam directions, except in a narrow sector about the difficult forward direction, where there appears to be a sidelobe floor of roughly –23 dB.

1. INTRODUCTION

In future aircraft it may be desirable to utilize the large aerodynamic areas of the wings also for electrodynamics by structurally embedding conformal phased array antennas. We explore the feasibility of this approach by analyzing an array of antenna elements wrapped around a wing. This is a generic case in that the line array allows scanning in a plane transverse to the wing only. However, it serves the two objectives of this study: 1) to develop a pattern synthesis method which is effective for this non-conventional array shape, and 2) to determine whether low sidelobe patterns can be realized.

2. THE ARRAY MODEL

In our computer model the wing is represented as a 2-dimensional infinite, conducting cylinder with a cross section equal to a wing profile typical of the SensorCraft air vehicle concept presently being considered by the AF Research Laboratory [1]. The array consists of 116 antenna elements distributed uniformly around this profile, see Fig. 1. The elements are taken to be microstrip patches, with center frequency 5.45 GHz, and are spaced uniformly with half-wavelength (λ/2) in an E-plane configuration.

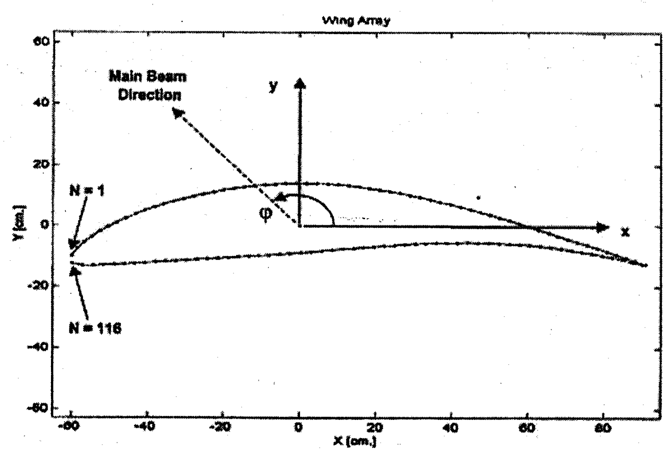

Figure 1 - Definition of element indices and main beam direction [1]

The elements were designed with the code CyMPA [2], which can model microstrip patches on dielectric covered, circular cylinders. The element geometry and the magnitude of the reflection coefficient $|S_{11}|$ versus frequency and radius of curvature are shown in Fig. 2 The narrow bandwidth is a consequence of choosing a thin substrate, which would be flexible enough to conform to the local radius of curvature.

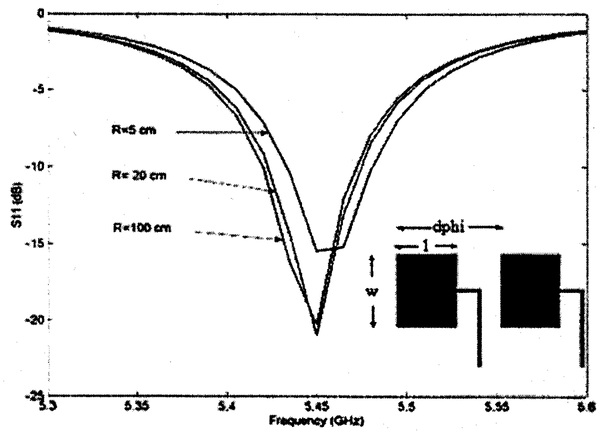

Figure 2 - Element design geometry and |S11| return loss versus radius of curvature [1]

Array element patterns $g_n(\varphi)$, which include mutual coupling effects, were also computed with this code by approximating each element and its neighbors with the corresponding, locally osculating circular array [3]. A further small approximation was incurred for cases where the radius of curvature was > 20λ or negative, in which cases the radius was set equal to 20λ. The reason is that CyMPA is based on an eigenfunction expansion which is limited to moderately large radii of curvature. Some representative element patterns are shown in Fig. 3.

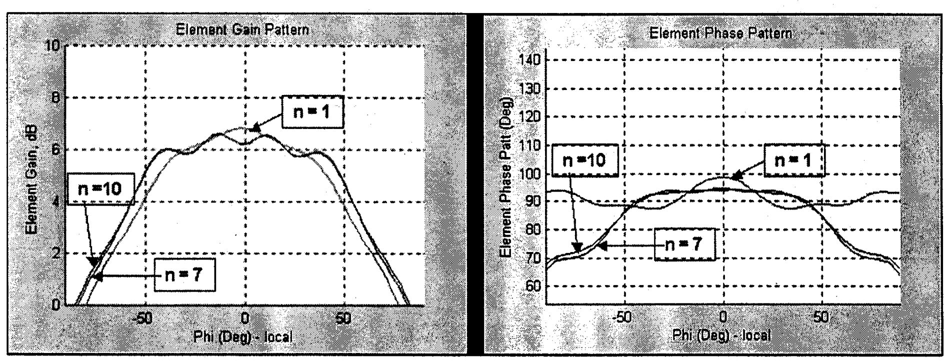

Figure 3 - Typical array element patterns [1]

3. Pattern Synthesis using Alternating Projections

We use a pattern synthesis method based on alternating projections [4]. This is an iterative numerical approach which offers great flexibility and handles both shaped beam and pencil beam synthesis and arbitrary sidelobe envelopes. We apply this method to synthesize power patterns, i.e. no constraints on the far field phase.

The method is illustrated in Fig. 4 which shows a set of desirable patterns F_d and a set of realizable patterns F_r, and where we alternately find the closest point (projection) on the two sets until a common point (or the particular point of the realizable set which is closest to the desirable set) is found.

Denoting by $g_n(\varphi)$ the field pattern of array element n in its array environment, the set of realizable patterns is represented by $F_r(\varphi) = \sum_1^N a_n \, g_n(\varphi)$, where a_n are arbitrary complex excitation coefficients of the N elements.

The set of desirable patterns may be represented by upper and lower bounds on the pattern, M_u (φ) and M_l (φ), as shown in Fig. 5, and a desirable pattern $F_d(\varphi)$ may be represented by the discrete set of samples $F_d(\varphi_m)$, $m=1...M$, $(M>>N)$. The iterations now proceed as follows:

$\underline{F_r(\varphi)\rightarrow F_d(\varphi)}$
From F_r the desirable pattern F_d is obtained by the rule, for $m=1,..,M$

if $M_l(\varphi_m)<|F_r(\varphi_m)|< M_u(\varphi_m)$ *then* $F_d(\varphi_m)= F_r(\varphi_m)$,

if $|F_r(\varphi_m)|< M_l(\varphi_m)$ *then* $F_d(\varphi_m)= M_l(\varphi_m)* F_r(\varphi_m) / |F_r(\varphi_m)|$,

if $|F_r(\varphi_m)|> M_u(\varphi_m)$ *then* $F_d(\varphi_m)= M_u(\varphi_m) *F_r(\varphi_m)/ | F_r(\varphi_m)|$.

$\underline{F_d(\varphi)\rightarrow F_r(\varphi)}$
From F_d the realizable pattern F_r is obtained by solving the overdetermined system of equations

$F_r(\varphi_m) \equiv \sum a_n\, g_n(\varphi_m) = F_d(\varphi_m) \quad m=1,..,M$

in the least-mean-square sense, which leads to a new set of $\{a_n\}$ and thus to a new $F_r(\varphi)$.

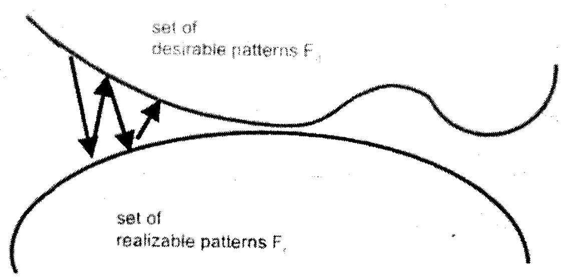

Figure 4 - Illustrating pattern synthesis using alternating projections

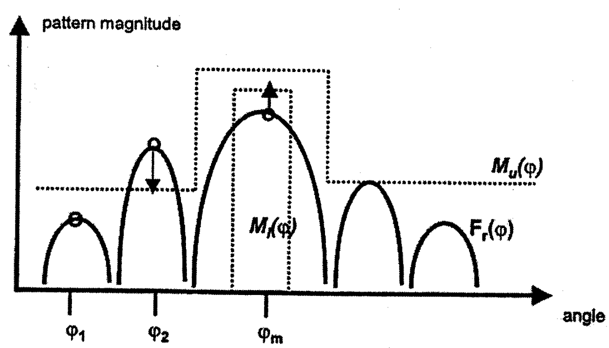

Figure 5 - The upper and lower bounds Mu(φ) and Ml(φ) define desirable patterns, Fr(φ) represents a realizable pattern.

A weakness of the method of alternating projections is that it may get hung in a local minimum (as represented by the parts on the far right of the sets in Fig. 4), if an unsuitable starting point is chosen. As a precaution therefore, we remove all excess phase variation in the element patterns by referencing them to a common phase center within the set of active array elements. As starting values, we then choose an element excitation, which is uniform in amplitude and focused in the desired main beam direction. So far, our results indicate that local minima do not pose a serious problem.

Convergence of the method is fast, usually a few hundred iterations were adequate, which only took seconds on a 1.5 GHz PC.

4. Results

Fig. 6 shows an example of a synthesized pattern for a 135 degree look direction, assuming elements 1-10 active (angle and element numbering as defined in Fig. 1).

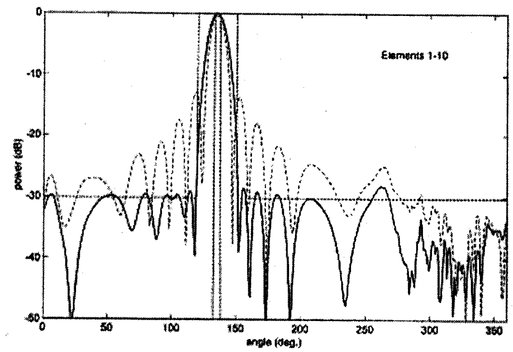

Figure 6 - Upper and lower bounds for the desired –30 dB sidelobe pattern (dotted) and realized pattern (solid). Uniform amplitude array focused at 135 deg. produces pattern with –13 dB sidelobes (dashed). 10 elements active. The look direction is forward, 45 degrees above the horizon.

These elements all have a local normal within ± 22 degrees from the desired look direction. A simple uniform amplitude array excitation focused in that direction produces the (normalized) pattern shown by the dashed line, and has close in sidelobes of about -13 dB. In order to obtain a pattern with lower sidelobes, say –30 dB, we impose the upper and lower desired pattern bounds $M_u(\varphi)$ and $M_l(\varphi)$, as shown by the dotted lines, and obtain via alternating projections the best realizable pattern, shown by the full line. In this case, the desired sidelobe level is practically achievable. Also, the synthesized array distribution seems very reasonable, see Fig. 7.

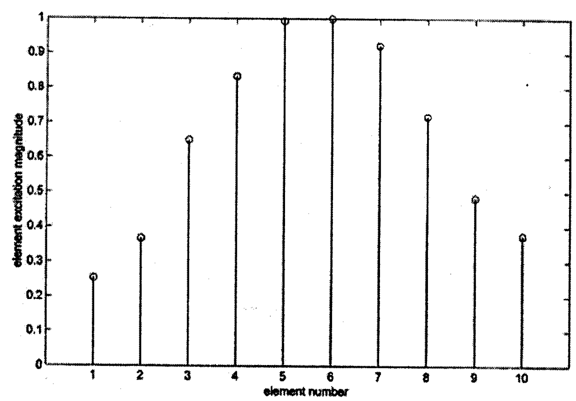

Figure 7 - Array excitation corresponding to the realized pattern

The high sidelobe of –28 dB at about 260 degrees is similar to a 'smeared out' grating lobe for our curved array and cannot be suppressed much further by lowering the desired sidelobe level or broadening the desired main beam. However, increasing the active array to include elements 1-15 is effective and allows this sidelobe to be reduced by roughly 9dB down to –37.5 dB, see Fig. 8.

Finally, we attempt to synthesize a beam in the forward direction ($\varphi \approx 180$ degrees), which is a difficult direction since the projected area of the array is small, and very few elements radiate efficiently in that direction. Employing the eight elements (No. 1-7 and 116), whose normals are within 60 degrees of the desired look direction, we find that the projected area is 13.5 cm ≈ 2.5 wavelengths, which corresponds to an expected null-to-null beam width of about 48 degrees. Setting the desired beam width equal to this estimate and gradually reducing the desired sidelobe level we find that we can realize patterns with a uniform sidelobe level of about -23 dB, as shown in Fig. 9 full line. At this look direction, it appears difficult to realize uniform sidelobe levels, which are significantly lower, although more elements allow for a considerably narrower main beam.

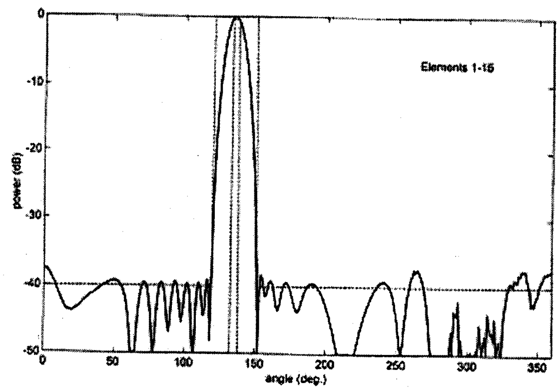

Figure 8 - A pattern with close to –40 dB sidelobes is realizable with 15 elements active

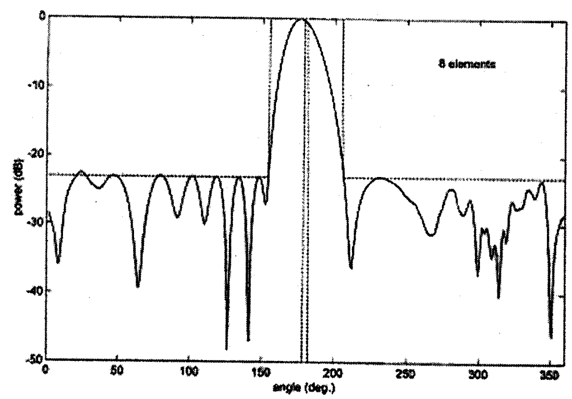

Figure 9 - With the main beam in the forward direction, where the projected aperture is minimum, a uniform sidelobe level of roughly –23 dB appears to be realizable, but not much more.Elements No. 1-7 and 116 active

5. Conclusion

We have explored pattern synthesis for a conformal wing array. The computer model is based on a representative wing profile and on array element patterns which include the effects of mutual coupling and the local radius of curvature. Therefore the computed patterns should be highly realistic in a plane transverse to the wing.

The infinite cylinder model ignores any scattering from the ends of a finite wing. However, a full wing array would have several of these line arrays in parallel, which increases the gain in the scan direction and reduces the illumination of the ends. Therefore, these end effects may indeed be negligible.

The pattern synthesis method based on alternating projections appears to be highly efficient for this non-conventional array shape, and no convergence problems due to local minima were observed.

High quality patterns with uniform low sidelobes are achievable for most beam directions. In a narrow sector about the difficult forward direction, where the projected aperture area is a minimum, there appears to be a sidelobe floor of roughly –23 dB. This presumably is the effect of the relatively large differences in the element patterns.

6. ACKNOWLEDGEMENT

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